Surface Resistivity Measurements of Candidate Subreflector Surfaces

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Subreflectors on DSN antennas have historically been of formed and welded sheet metal construction, which is quite costly. Flame-spray metallized fiberglass-epoxy offers an alternative technique at much lower cost. This article presents results of a study to show that system noise temperature would be increased about 0.3 K at X-band when using the alternate material. Additional testing, however, is required to evaluate weathering and noise generation while diplexing at high power.

I. Introduction

In support of a study to find low-cost alternative materials for subreflector surfaces, a work order was issued to the Harris Corporation of Melbourne, Florida, to (1) purchase samples of flame-spray metallized fiberglass-epoxy materials, (2) construct a test cavity to JPL specifications, (3) perform measurements in accordance with JPL procedures, (4) reduce the data taken, and (5) prepare a test report. Except for Section VIII, this article is primarily a copy of the test report by C. W. Choi and G. J. Kirkpatrick of the Harris Corporation.

II. Cavity and Samples

A TE_{011} cavity resonator technique, developed by Clauss and Potter of JPL (Ref. 1), was the measurement technique used by Harris Corporation for the evaluations of low-cost alternative materials. The drawing supplied by JPL for the cavity resonator is shown in Fig. 1. Unavailability of a large block of copper made it necessary to find another suitable high-conductivity metal to make the cavity. Silver-plated brass was selected instead of aluminum owing to the higher cavity Q-values obtainable with this plated material. The top lid of the cavity is formed by laying a flat test sample on top of the cavity.

Flat sheet test samples were made from the following materials:

(1) Copper.

(2) Aluminum 6061-T6.

(3) Aluminum 2024-T3.

(4) Standard flame-sprayed aluminum on fiberglass substrate.

(5) Standard flame-sprayed copper on item 4 (resulting in a metallized surface consisting of copper over aluminum).

(6) Buffed, flame-sprayed aluminum on fiberglass substrate.

(7) Standard flame-sprayed copper on item 6 (resulting in a metallized surface consisting of copper over buffed aluminum).

Three sets of 4- × 4-in. samples were made for each of the materials in order to determine the repeatability of the Q-value measurements of each kind of sample. A silver-plated brass plate was used as the reference material in the calculation of the surface resistivity of each sample.

III. Experimental Setup

A test setup block diagram for precision Q-measurement is available from a JPL report (Ref. 1). Since the available test equipment did not exactly match that listed in the JPL report, the revised test setup shown in Fig. 2 was adopted. This arrangement did not allow swept-frequency display, but because of the synthesized signal generator (HP 8672A) and precision attenuators (HP H382A), highly accurate data could be taken on a point-by-point basis.

Some pertinent electrical characteristics for major test apparatus are shown below:

(1) HP 8672A synthesized signal generator frequency resolution: 2 kHz at X-band.

Time base: internal 10 MHz ($<5 \times 10^{-10}$/day aging rate).

(2) HP H382A variable attenuator accuracy: ±0.2% of reading or 0.1 dB, whichever is greater.

(3) HP 8410B/8412A/8411A network analyzer accuracy: 0.08 dB/dB from midscreen. (Note that all the measurements were done at the midscreen employing two variable attenuators HP H382A.) The dual channel scheme of the network analyzer significantly reduces amplitude variation errors from the signal generator.

IV. Measurement and Results

The loaded Q of the cavity was obtained from

$$Q_\ell = \frac{F_0}{\Delta F} \tag{1}$$

where F_0 is the resonant center frequency and ΔF is the 3-dB frequency spread. The approximate center frequency and a pair of frequencies each for the 2-, 3-, and 4-dB points were recorded. The 3-dB point measurements were repeated and the peak power level checked again. All of these measurements were taken at the midscreen of the network analyzer using two precision variable attenuators to make accurate amplitude measurements. No attempt was made to utilize the phase information of the network analyzer since it is redundant. To insure the repeatability of the measurement, three sets of samples were tested. The center frequency was calculated from the average of the 3-dB points, since the frequency response of the test cavity near resonance is relatively flat. The insertion loss at the center frequency was measured, using one of the variable precision attenuators, after the frequency response of the cavity was measured.

Once these data were collected for each sample, the loaded Q was calculated from Eq. (1) and the unloaded Q was obtained from Eq. (15) of Ref. 1, given below as

$$Q_0 = Q_\ell \left(\frac{L^{1/2}}{L^{1/2} - 1} \right) \tag{2}$$

where L is the transmission power loss ratio. The following expression given in Ref. 1

$$Q_0 = \frac{\left(\frac{\pi}{2}\right) Z_0 \left(\frac{\lambda_c}{\lambda_0}\right)^2 \left(\frac{\lambda_g}{\lambda_0}\right)}{\left[R_{s_{cyl}} \left(\frac{\ell}{a}\right) + \left(\frac{\lambda_c}{\lambda_g}\right)^2 \left(R_{s_{end1}} + R_{s_{end2}}\right)\right]} \tag{3}$$

was employed to calculate the surface resistivity where

$Z_0 = 120\,\pi$, ohms

ℓ = length of cavity

a = radius of cavity

$\lambda_c = a/0.610$

$\lambda_g = 2\ell$

R_{s_x} is the surface resistivity of the location designated by x.

First the surface resistivity of the reference sample, a silver-plated brass plate, was calculated from Eq. (3). This value was subsequently used for $R_{s_{cyl}}$ and $R_{s_{end1}}$ in order to calculate the value of $R_{s_{end2}}$ for the other samples of each set. These were tabulated for each set and are shown in Tables 1 through 3 along with the measured data.

Examination of this data showed that the value of the surface resistivity of the silver-plated brass was reasonable. The value shown for copper falls between the two experimental figures given for copper in Ref. 1. However, the aluminum samples showed an unusually low value of resistivity, the 2024-T3 differing by about 20% from the sample JPL data on 2024 alloy of unknown T-value. The values for the flame-sprayed samples could not be compared owing to the lack of published data.

A possible explanation for the aluminum measurement could be a disparity between the surface characteristics of the reference silver-plated brass plate and the interior of the cavity.

To eliminate this possibility, a new brass plate was fabricated, and both the plate and cavity were polished to a uniform surface roughness, then simultaneously plated with about 10 skin depths of silver. The cavity coupling was increased to about 15 dB for the silver-plated brass plate, a 10-dB pad was inserted on each side of the test cavity for improved isolation, new data were obtained and the results were tabulated. Comparing the data to the original set, a rather uniform reduction in surface resistivity was observed, the average downward shift being about 0.00243 ohms. To insure the integrity of the sample surfaces, several of them were cleaned. Four of the aluminum plates were cleaned in trichloroethylene, nitric acid, and water while another two were cleaned in alcohol. Two copper plates were cleaned in trichloroethylene, hydrochloric acid, and water while another was cleaned in alcohol, as shown in Tables 4-6. The cleaning had a negligible effect on the results.

V. Measurement Accuracy

As mentioned in the experimental setup section there are errors associated with the equipment. One source of error is the measurement of the 3-dB frequency spread. The precision variable attenuator has a possible error of 0.1 dB at the 3-dB point. In addition, the error involved in resetting to the mid-screen of the network analyzer is on the order of 0.01 dB. With ±0.11 dB maximum error for the 3-dB measurement and the approximate slope of the frequency response of the test cavity, the error in the value of Q_ℓ can be bounded. The maximum error in the dB reading of the transmission loss ratio (L, dB) is 0.1 dB and an additional 0.01 dB due to resetability. Except for the error of 0.01 dB in resetting, the errors mentioned above are not random errors, but errors inherent in the equipment.

Experimentally, examining the slope of the frequency response, the error involved in the 3-dB frequency spread due to the possible 0.11-dB deviation was found to be less than 0.026 ΔF. Thus the error involved in the loaded Q value (Eq. 1) was less than 2.7%. The error involved with the measurement of the transmission loss ratio resulted in less than 0.28% error in the calculation of the unloaded Q (Eq. 2) in any one of the samples. Additional unaccounted for errors such as variations in temperature and humidity may be estimated by examining Tables 1, 2, and 3 side by side. Maximum deviation of the values of unloaded Q for any particular material is less than 1.36% for the first three sets of data shown in Tables 1, 2, and 3. The gross estimation of cumulative error due to all effects appears to be less than 10%. The 20% variance between the measured resistivity of aluminum and the published values remains to be explained. The three sets of seven samples were sent to JPL for possible verification.

VI. Summary of Resistivity Measurements

Table 7 summarizes the surface resistivity measurement results of all six runs for each material tested. More detailed data can be found in Tables 1 through 6.

VII. Microwave Performance Effects

Subsequent to receiving the resistivity results from Harris Corporation, JPL calculated the system temperature contribution which would be caused at X-band by the surface resistivity of each of the materials using the approximate formula for normal incidence angle (Ref. 2)

$$N_t \approx \frac{4R_s}{Z_0} T_p \tag{4}$$

where

$Z_0 = 120\,\pi$ ohms

$T_p = 290$ K

Table 8 shows these results.

Typically, DSN subreflectors have been made from 6061-T6 aluminum material which gives a system noise temperature contribution of 0.117 K at X-band. If buffed flame-sprayed aluminum on fiberglass substrate were used for the subreflector material, its contribution would be 0.391 K resulting in a net system temperature increase of approximately 0.27 K at X-band.

VIII. Conclusion

Use of the low-cost materials would cause a small increase in system temperature while providing a large reduction in the procurement cost. However, before selecting these materials for use in the DSN, additional studies are required to ensure that the surface resistivity does not degrade with extended weathering. Another factor which requires evaluation for antennas which also transmit is possible noise that is generated while diplexing. In the final fabrication, quality assurance steps need to be taken to ensure that the plating thickness is at least 5 skin depths at the lowest S-band (or L-band) frequency at which the subreflector will be used.

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References

1. Clauss, R., and Potter, P. D., "Improved R.F. Calibration Techniques – A Practical Technique for Accurate Determination of Microwave Surface Resistivity," Technical Report 32-1526, Vol. XII, pp. 54-67, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1972.
2. Otoshi, T., *IEEE Trans. Instrumentation and Measurement*, Nov. 1972, p. 451 (Use Eq. (3) for zero diameter hole case.)

Table 1. Run 1, first set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass	8426.842	0.392	21497	21.8	23399	0.02777
Copper	8417.791	0.394	21365	21.7	23279	0.02795
Aluminum 6061-T6	8428.158	0.440	19155	22.6	20689	0.03987
Aluminum 2024-T3	8428.632	0.424	19879	22.3	21531	0.03582
Standard flame-sprayed aluminum	8426.427	0.854	9867	28.25	10264	0.1455
Standard flame-sprayed aluminum and copper	8417.341	0.682	12342	26.5	12955	0.1014
Buffed flame-sprayed aluminum	8417.545	0.790	10655	27.5	11124	0.1286
Buffed flame-sprayed aluminum and copper	8419.627	0.694	12132	26.6	12727	0.1045

Table 2. Run 2, second set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass	8428.279	0.394	21392	21.6	23332	0.02787
Copper	8420.616	0.392	21481	22.6	23201	0.02814
Aluminum 6061-T6	8428.683	0.438	19244	22.5	20804	0.03910
Aluminum 2024-T3	8428.738	0.424	19879	22.2	21552	0.03550
Standard flame-sprayed aluminum	8427.374	0.856	9845	28.2	10244	0.1457
Standard flame-sprayed aluminum and copper	8416.108	0.680	12377	26.9	12962	0.1010
Buffed flame-sprayed aluminum	8427.564	0.780	10805	27.6	11275	0.1265
Buffed flame-sprayed aluminum and copper	8417.311	0.694	12129	26.5	12731	0.1041

Table 3. Third set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass	8428.785	0.394	21393	21.7	23309	0.02790
Copper	8435.023	0.394	21409	22.0	23256	0.02832
Aluminum 6061-T6	8428.758	0.440	19156	22.6	20690	0.03960
Aluminum 2024-T3	8427.930	0.424	19877	22.3	21529	0.03551
Standard flame-sprayed aluminum	8423.660	0.856	9841	28.5	10225	0.1458
Standard flame-sprayed aluminum and copper	8414.552	0.688	12230	26.5	12838	0.1024
Buffed flame-sprayed aluminum	8427.631	0.786	10722	27.7	11183	0.1280
Buffed flame-sprayed aluminum and copper	8415.836	0.698	12057	26.7	12642	0.1051

Table 4. Run 4, first set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass	8423.297	0.382	22051	15.4	26561	0.02449
Copper[a]	8417.284	0.380	22151	16.0	26337	0.02500
Aluminum 6061-T6[a]	8425.422	0.424	19871	16.5	23358	0.03568
Aluminum 2024-T3[a]	8425.776	0.416	20254	16.1	24017	0.03316
Standard flame-sprayed aluminum	8423.785	0.854	9864	22.2	10694	0.1449
Standard flame-sprayed aluminum and copper	8415.310	0.676	12449	20.5	13746	0.09965
Buffed flame-sprayed aluminum	8423.511	0.786	10717	21.6	11683	0.1278
Buffed flame-sprayed aluminum and copper	8415.649	0.686	12268	20.6	13530	0.1022

[a]Chemically cleaned.

Table 5. Run 5, second set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass (polished)	8422.908	0.384	21935	15.4	26453	0.02481
Silver-plated brass (unpolished)	8424.378	0.384	21938	15.4	26414	0.02497
Copper[a]	8415.636	0.388	21690	15.0	26381	0.02482
Aluminum 6061-T6[a]	8425.615	0.430	19594	16.6	23019	0.03704
Aluminum 2024-T3[a]	8425.428	0.416	20253	16.1	24016	0.03315
Standard flame-sprayed aluminum	8421.993	0.846	9955	22.0	10809	0.1426
Standard flame-sprayed aluminum and copper	8412.003	0.682	12334	20.2	13670	0.1003
Buffed flame-sprayed aluminum	8424.718	0.780	10801	21.6	11787	0.1262
Buffed flame-sprayed aluminum and copper	8411.249	0.690	12190	20.3	13498	0.1023

[a]Chemically cleaned.

Table 6. Run 6, third set of samples

Sample	F_0, MHz	ΔF, MHz	Q_ℓ	L, dB	Q_0	R_s, Ω
Silver-plated brass	8420.424	0.380	22159	15.8	26434	0.02479
Copper[a]	8432.156	0.380	22190	16.4	26174	0.02595
Aluminum 6061-T6[a]	8426.163	0.426	19780	17.0	23055	0.03692
Aluminum 2024-T3[a]	8425.732	0.412	20451	16.6	24001	0.03322
Standard flame-sprayed aluminum	8423.786	0.848	9934	22.4	10749	0.1438
Standard flame-sprayed aluminum and copper	8411.620	0.664	12668	21.0	13915	0.09755
Buffed flame-sprayed aluminum	8424.558	0.780	10801	21.4	11799	0.1260
Buffed flame-sprayed aluminum and copper	8412.476	0.684	12299	20.4	13606	0.1011

[a]Cleaned with alcohol.

Table 7. Summary of resistivity data at 8.43 GHz (see Tables 1–6 for actual frequencies)

Sample	Lowest R_s, Ω	Highest R_s, Ω	Average R_s, Ω
Silver-plated brass	0.02449	0.02790	0.02627
Copper	0.02482	0.02832	0.02670
Aluminum 6061-T6	0.03568	0.03987	0.03804
Aluminum 2024-T3	0.03315	0.03582	0.03439
Standard flame-sprayed aluminum	0.1426	0.1458	0.1447
Standard flame-sprayed aluminum and copper	0.09755	0.1024	0.1004
Buffed flame-sprayed aluminum	0.1260	0.1286	0.1272
Buffed flame-sprayed aluminum and copper	0.1011	0.1051	0.1032

Table 8. Average resistivity and noise temperature contributions at 8.43 GHz

Material	Average resistivity, Ω	Noise contribution, K
Silver-plated brass	0.02627	0.081
Copper sheet	0.02670	0.082
6061 T6 aluminum	0.03804	0.117
2024 T3 aluminum	0.03439	0.106
Standard flame-sprayed aluminum	0.1447	0.445
Standard flame-sprayed aluminum and copper	0.1004	0.309
Flame-sprayed aluminum (buffed)	0.1272	0.391
Flame-sprayed aluminum and copper (buffed)	0.1032	0.318

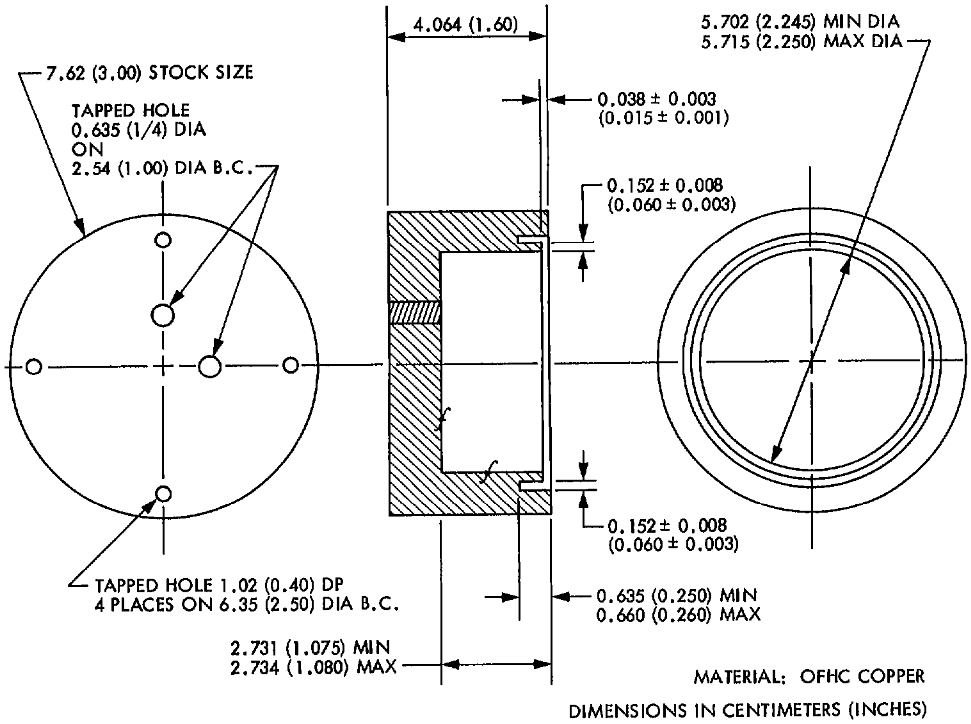

Fig. 1. Cavity dimensions. Note: Required inside surface finish is 40 microcm (16 microinch) or better

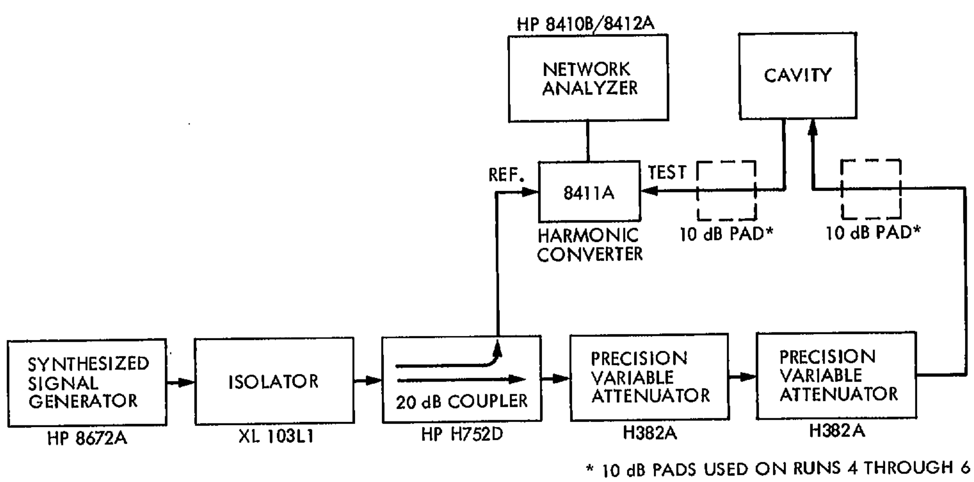

Fig. 2. Test setup